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SEISMIC STUDIES OF REGIONAL PATH PROPERTIES OF EURASIA

ILENE R. SAMOWITZ
DAVID M. HADLEY

ANNUAL TECHNICAL REPORT
PART I

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The goal of this study has been to improve the basis for predicting regional path properties encountered by surface waves propagating in Eurasia. At regional distances the observed seismograms are severely influenced by seismic structure along the path between the source and the receiver. Accurate earth models therefore play a critical role in the ability both to detect small events and to discriminate between earthquakes and explosions. Once the regional earth properties and the mode of seismic wave propagation are well

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understood, seismic source characterization will be much more reliable. The successful completion of modeling regional seismic surface waves requires several steps: (1) construct starting models for each geologic province that are based on a review and synthesis of the geologic and seismic literature; (2) review and collect seismic data for paths crossing each geologic province; (3) reduce the seismic data to group and phase velocity dispersion curves; (4) invert the dispersion data to improve the regional models. This report summarizes work completed during the first year of a two-year effort. Although several path averaged models that match the observations have been derived during this contract year, the primary emphasis has been in the first three tasks listed above. Completion of the dispersion analysis and regionalized inversion of these data will be carried out during the next contract year.

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I. SUMMARY AND CONCLUSIONS

1.1 SUMMARY

The goal of this study has been to improve the basis for predicting regional path properties encountered by surface waves propagating in Eurasia. At regional distances the observed seismograms are severely influenced by seismic structure along the path between the source and the receiver. Accurate earth models therefore play a critical role in the ability both to detect small events and to discriminate between earthquakes and explosions. Once the regional earth properties and the mode of seismic wave propagation are well understood, seismic source characterization will be much more reliable. The successful completion of modeling regional seismic surface waves requires several steps: (1) construct starting models for each geologic province that are based on a review and synthesis of the geologic and seismic literature; (2) review and collect seismic data for paths crossing each geologic province; (3) reduce the seismic data to group and phase velocity dispersion curves; (4) invert the dispersion data to improve the regional models. This report summarizes work completed during the first year of a two-year effort. Although several path averaged models that match the observations have been derived during this contract year, the primary emphasis has been in the first three tasks listed above. Completion of the dispersion analysis and regionalized inversion of these data will be carried out during the next contract year.

1.2 RECOMMENDATIONS AND CONSIDERATIONS FOR PROJECT COMPLETION

This project was designed and scheduled as a two-year effort. During the next contract period the phase velocity determinations for the paths shown on Figure 2 will be finalized. The data set should also be augmented with digital data from SRO and other high quality seismic stations. To date, only data from presumed nuclear explosions have been used in the analysis. If a particular region of interest is poorly sampled by this data set, natural sources should be used to fill in the gaps. Before earthquake data could be used, the source characteristics would have to be determined from body wave studies.

After the phase velocity curves for each path have been determined, the next step in the project should be a regionalized inversion. This analysis will decompose the phase curves into the contributions from each geologic province as defined on Figure 1. Finally, these individual phase curves can be inverted for structure and compared directly with the literature models. This last step will be quite important for assessing the accuracy and reliability of the Russian literature for characterizing regional path properties.

By defining the basic characteristics of the crust and upper mantle within each geologic province from literature starting models, and refining these models with longer period surface wave studies, the next major step will be to

fine-tune these models with high frequency data such as Lg. The approach of modeling first the longer period components and then the high frequency complex regional crustal phases provides the best approach to accurately model the wave propagation phenomena.

II. INTRODUCTION

In order to study paths transversing the USSR, it is convenient to subdivide Eurasia into tectonic units. The first step in this study has been an extensive search of the available geologic and geophysical literature describing the crust and upper mantle structure of the USSR and Eurasia. During the past twenty-five years a vast amount of deep seismic sounding (DSS) has been done in the USSR. We attempted to fully use source material from the Soviet literature that have resulted from this massive campaign, as well as previously unavailable Russian data that have been organized and critiqued by Piwinskii (1979).

From this broad data base, the USSR was subdivided into eleven distinct tectonic provinces (Figure 1). The boundaries for these provinces were drawn after considering geologic evolution, seismic activity, heat flow, Moho properties, crustal properties, seismic wave velocities, attenuation, gravity, regional phase propagation and upper mantle structure. The major emphasis of this regionalization has been on seismic properties. It is important to point out that crustal properties are not uniform in each individual province but that each region represents a coherent evolutionary unit. From this regionalization, "literature starting models" were derived for each province. We will summarize some of these findings in this report, however, a full discussion of this regionalization is available in "Summary and Review of the Tectonic Structure of Eurasia, Part I," by Samowitz and Hadley (1980).

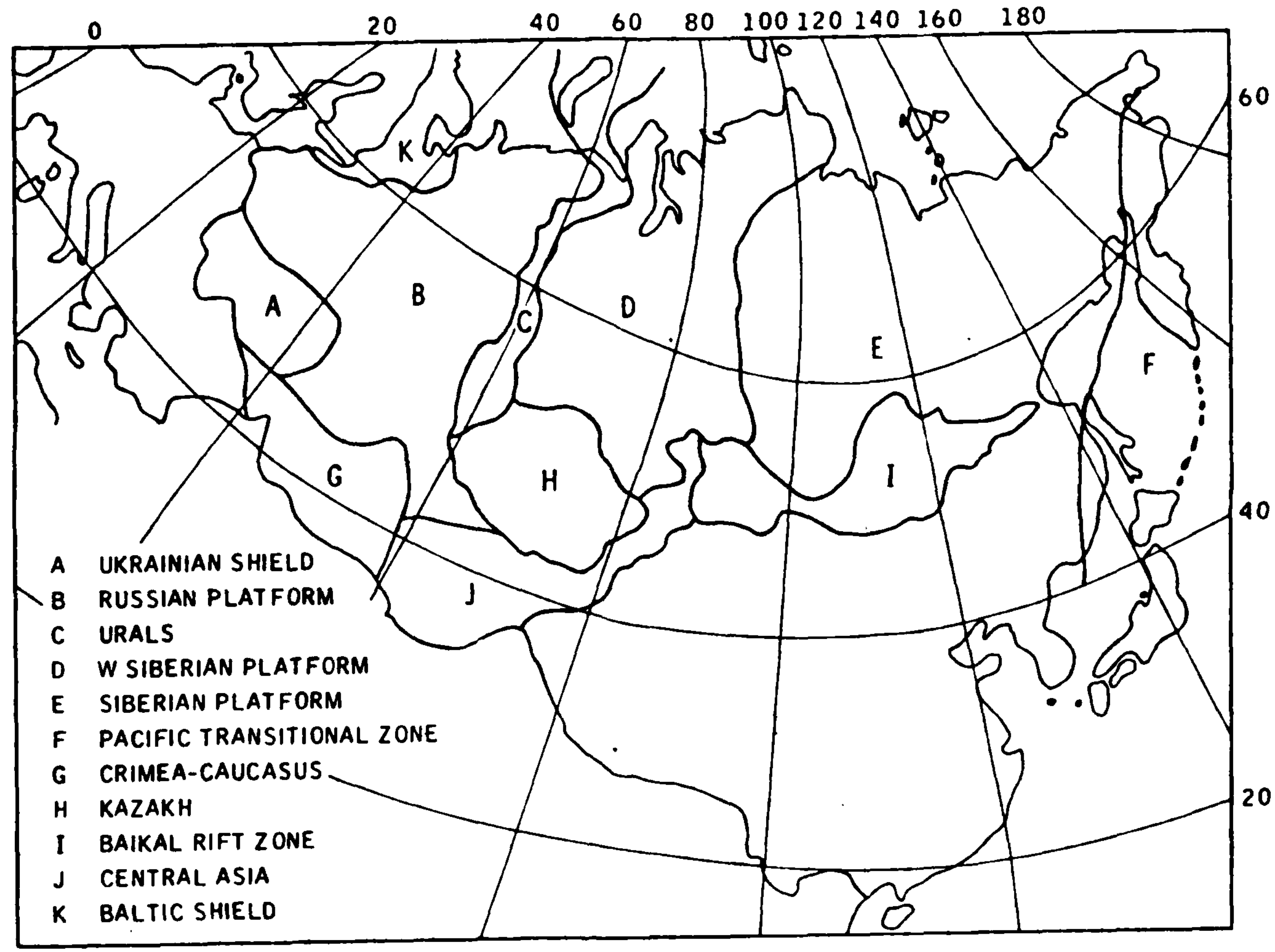

Figure 1. Tectonic provinces of the USSR.

These regionalized starting models have been refined in this study through analysis of surface wave data. This study used surface wave data from presumed nuclear explosions located within the Soviet Union that have been recorded at WWSSN Stations in both Europe and Asia. Rayleigh waves that were recorded at WWSSN stations were used to determine the group and phase velocities along these paths. Because explosions do not usually excite very long period surface waves, the following discussion is restricted to the period range of 5 to 100 seconds. Derived phase velocities were finally inverted for the crustal structure (final model) using a damped linear inverse method. The paths used were generally less than 2500 km. By using shorter paths it is easier to compare our final model with the starting literature models. Synthetic seismograms were computed for each final model and compared with the original seismograms.

The synthetic Rayleigh waves calculated from our final model do an extremely good job in matching the observed seismograms. In contrast, synthetics calculated from the literature starting models are in poor agreement with the observations. The literature models differ from our final models. We believe this is mainly due to the following factors:

a) Inconsistencies in the Soviet DSS literature

b) Lack of data along paths of each region

c) Lateral variations in crustal structure

The following sections discuss geologic regionalization, the data base, the data analysis and inversion process, comparisons to synthetic seismograms with observations and recommendations and considerations for project completion.

III. REGIONALIZATION

The provinces within Eurasia are extremely diverse, for example, there are old stable regions such as the Baltic and Ukrainian Shields as well as extremely young and active regions such as the Pacific Transitional Zone and Soviet Central Asia. Properties of these regions vary significantly. For example, Moho depths range from 8 km in the Pacific Transitional Zone to 80 km in Central Asia. Pn velocities vary from 7.6 km/sec in the Baikal Rift Zone to 8.5 km/sec in Kazakh.

It is extremely important to note that, when reviewing deep seismic sounding data, many ambiguities arise from the different interpretations of the data. When reviewing each province the velocities and depths found most frequently for the region were considered to be the norm. Areas with slightly differing tectonic histories or geophysical characteristics were categorized as subregions. Subregions were not developed when data were scarce.

3.1 SHIELDS

There are two different shield provinces within the USSR, the Ukrainian Shield and the Baltic Shield. These shields are tectonically stable and consist of crystalline and highly metamorphic rocks in which granitoids, gneisses, migmatites, and granites of Archean-Proterozoic age are predominant.

UKRAINIAN SHIELD

The crustal thickness in the Ukrainian Shield ranges from 30 km to 50-65 km. Areas that have thick crust are associated with roots of mountain systems which existed in Proterozoic time. Places which the Moho does not exceed 30-40 km are considered to be ancient platforms.

The earth's crust in the Ukraine is crudely layered. The average velocity in the sedimentary layer is 2.5 km/sec, in the granitic layer 6.3 km/sec, and in the basaltic layer 7.0 km/sec yielding an average crustal velocity of 6.7 km/sec (Vol'vovskii, 1978). These are average velocities in each layer, however, the velocities increase with depth. When the Moho is at 49 km depth, Pn values are 8.1 to 8.2 km/sec and at 60 km depth, Pn values are 8.6 km/sec (Sollogub, et al., 1978). There are several fault systems which penetrate the crust and upper mantle forming a block-like structure.

BALTIC SHIELD

The crust in the Baltic Shield is a block-like structure, with each block interpreted as an independent structure of the same volcanic cycle. As a rule, blocks are bounded by faults. The marginal parts of each block may be involved in subsequent younger tectonic movements. When this occurs, the boundaries are usually indistinct. Proterozoic structures are found such as troughs, graben-type synclines, fault monoclines as well as complex Archean synclines and anticlines.

The Baltic Shield has a crustal thickness ranging from 30-43 km with a mean value of 35 km (Sologub, et al., 1973b). The principal boundary is the Moho with an average Pn velocity of 8.1-8.2 km/sec. The Baltic Shield has a smaller crustal thickness than the Ukrainian Shield, suggesting a longer period of uplift which has resulted in a deeper erosion of the crust.

3.2 PLATFORMS

There are three different platform regions in the USSR, the Russian Platform, the Western Siberian Platform, and the Siberian Platform. Platforms are tectonically stable and are characterized by smooth gentle crustal interfaces. Crustal thicknesses usually range between 35 and 50 km. There are many deep fault systems throughout these platforms that penetrate the crust and upper mantle which result in block-like structures.

RUSSIAN PLATFORM

The Russian Platform has several structural units, most of which are basins. The Russian Platform began forming in the Proterozoic when large areas of consolidated Archean platform folded. Extensive subsidence and sedimentation occurred in most regions primarily in the Paleozoic. The North Caspian Basin subsided throughout the Permian and Mesozoic when it received 4-10 km of sediments. The whole platform was gently uplifted in the Quaternary. The Dnieper-Donetz depression formed in the Riphean as a result of extension in the upper part of the consolidated crust. During the Paleozoic, renewed extension formed a Hercynian graben over the Riphean trough-like structure. The Dnieper-Donetz trench is thought to be an analogue of an ancient rift (Kosminskaya and Pavlenkova, 1979; Borodulin, et al., 1978)and is often compared with the Red Sea.

The crustal structure within this region is not uniform. Most studies find that the crust has three continuous layers. However, depending on the subregion, there is a wide variation about the thickness of these layers. Crustal thicknesses tend to range between 35 and 50 km, and Pn velocities ranging between 8.0-8.2 km/sec. Kosminskaya and Pavlenkova (1979) published a cross section of the Dnieper-Donetz trench showing a decrease in Pn velocity directly under the depression to 7.8 to 7.9 km/sec compared to Pn velocities of 8.0-8.2 km/sec in nearby regions. However, they believe that this decrease in velocity may be an artifact of the data.

Several studies include a low velocity layer in the upper mantle. The depth and extent of this low velocity zone varies significantly depending on the researchers and regions studied. Masse and Alexander (1974) include a low velocity zone at 100 km with a P-wave velocity of 8.0 km/sec. King and Calcagnile (1976) show no low velocity layer in this region. Given and Helmberger (1980) include a low velocity zone between 150 and 200 km with P-wave velocities of 8.0 km/sec. Vinnik and Ryaboy (1980) found differences in the uppermost mantle between the northeast Russian platform and the North Caspian Sea depression. In the Russian platform they found a low velocity zone at a depth of 60 to 110 km with a P-wave velocity of 8.0 km/sec. In the North Caspian Depression they found the low velocity layer at 60-70 km with a P-wave velocity of 8.1 km/sec.

WESTERN SIBERIAL PLATFORM

The Western Siberian Platform is located to the east of the Urals and to the northeast of Kazakh. Alverson, et al. (1969) summarize the geology, tectonics, and structure. They believe that the platform has been generally stable since the Paleozoic. The margins of the platform have undergone geosynclinal deposition and orogeny in north trending belts, with Riphean folding in the east, early Proterozoic folding in the south, and late Paleozoic folding in the north and west. For the most part the basement is not exposed. The center of the platform probably is com-

posed of Pre-Cambrian gneiss, the eastern part of low grade Riphean schist, and the southern and western part of weakly metamorphosed Paleozoic sediments and volcanics. The general characteristics and tectonics of the Western Siberian Platform are not very well documented in the literature. References on the whole are fairly sparse in comparison with other regions.

Several studies indicate that there are three continuous crustal layers. The sedimentary layer is believed to be 3 to 4 km thick with P-wave velocities ranging between 2.6 km/sec to 5.5 km/sec. The thickness of the granitic crust ranges between 10 and 22 km with P-wave velocities ranging between 6.2 km/sec and 6.5 km/sec. The basaltic layer ranges in thickness between 10 and 22 km with P-wave velocities ranging between 6.7 km/sec and 7.1 km/sec. The crustal thickness ranges between 34 and 47 km with Pn velocities ranging between 7.9 and 8.2 km/sec.

SIBERIAN PLATFORM

The Siberian Platform is a massive province which consists of several subregions with differing tectonic backgrounds. The entire province is generally marked by complex fold systems and igneous intrusions. The age of formation of these subregions vary substantially. For example, the Anabar Shield is an Archeozoic structure, whereas, the Kolyma-Omolan stable block has been a platform region since early Proterozoic until it was uplifted in the

Mesozoic followed by a period of faulting and volcanism. This province tends to be nearly aseismic with the exception of the Verkhoyansk and Chaun-Chukotsk Foldbelt. This subregion has many deep faults situated within the folded regions of Stanovik-Dzhugdehur and in the marginal parts of the Aldan Shield. There has been repeated movement along these faults forming folds of several orders, ancient uplifts and sunken blocks bounded by deep faults in this province.

A summary of DSS for this region shows substantial variation in crustal thicknesses. Piwinskii (1979) summarizes the following findings. In the vicinity of Norilsk, the crust is crudely layered and has a thickness ranging from 35 to 40 km. Near the Aldan Shield there is also crude layering with crustal thicknesses ranging from 40 to 47 km. In both of these regions there are no deep fracture systems penetrating into the upper mantle. The crust in the vicinity of the Irkutsk amphitheater and Yakutsk have similar properties. The crust is crudely layered with thicknesses ranging from 33 to 46 km. The surface of the Moho in both regions is almost flat, exhibiting little relief. Additionally, deep fractures penetrate down to the upper mantle which result in a block-like structure. In the region of the Tunguss Syncline and in the northeastern folded regions the crust is slightly thinner with thicknesses of 29 to 39 km. Several deep fractures also occur in these regions. Several fractures penetrate as deep as the

upper mantle in the Tunguss Syncline while only one fracture penetrates into the upper mantle in the northeastern folded region.

TECTONIC REGIONS

The tectonic regions are broken up into two categories, older and younger tectonic regions. The Urals and Kazakh comprise the older tectonic regions, while Russian Central Asia, the Baikal Rift Zone, and the Pacific Transitional Zone comprise the regions. The young tectonic regions are characterized by high seismicity. In comparison, the two older provinces are nearly aseismic. However, they are grouped with these tectonic regions because their tectonic history is considerably younger than shields or platforms. The Urals is an old mountain system, whereas Kazakh has a complex history of folding with some uplifting.

URALS

The Ural fold system consists primarily of ultrabasic rocks and their associated gabbros and amphibolites. The Urals' analogue in North America is the Appalachians. The Urals and the Appalachians are similarly situated relative to ancient platforms and are broken up into two segments by deep faults. According to deep seismic sounding, the crustal thickness ranges from 38-50 km, with a mean value of 42 km. A summary of DSS profiles found in Vol'vovskii and Vol'vovskii (1978) indicates that the average thickness of

the top layer is approximately 7 km with an average P velocity of 5.5 km/sec. A thin high velocity layer, Vp=6.7-7.0 km/sec, thickness of 12 km, is intermittently found within the region at a depth of 7-8 km. The third layer has a thickness of approximately 10 km with a mean P-wave velocity of 6.4 km/sec. Pn velocities range from 8.2 km/sec to 8.3 km/sec.

McCowan, et al. (1978) model the crust and upper mantle for Novaya Zemlya. There is little available information in this region, but it is believed to be a northern extension of the Urals. Their model has a 45 km thick crust, a Pn velocity of 8.18 km/sec, and a shear wave low velocity zone in the upper mantle.

KAZAKH

Kazakh contains extensive areas of Archean and Proterozoic gneiss, schist, amphibolite with smaller amounts of quartzite and marble. This region began in the Riphean and Paleozoic as a geosyncline. By the Silurian, this region was largely mountainous with intermittent basins of continental sedimentation and extensive terrestial volcanism. The region is considered to be relatively stable since the Paleozoic.

Piwinskii (1979) subdivides the DSS data from Kazakh into four regions. Southeast Kazakh is reported to have a crustal thickness that varies between 40 and 60 km. There are several deep fault systems that penetrate the crust and

upper mantle. Due to the abundance of these fracture systems, the earth's crust is broken into block structures. The Moho in this region is characterized by mild relief and the Pn velocity is reported to be 8.1 km/sec. Crustal thickness in central Kazakh ranges from 40 to 54 km. Additionally, there are many deep fracture systems that penetrate the upper mantle. Pn velocities are reported to range from 8.0-8.5 km/sec. The crustal thickness varies between 35 to 50 km in west and southwest Kazakh. The Moho has little relief and is found at a depth of 40 to 46 km. Pn velocities range between 7.9 to 8.5 km/sec. Northwest Kazakh has many salt domes in the upper 5 kilometers of the crust. The crustal thickness in this region is reported to be between 38 to 42 km, indicating the flattest Moho in the entire Kazakh province. There are also fewer deep fault systems in this region.

3.3 RUSSIAN CENTRAL ASIA

The Russian Central Asia region is noted for its high seismicity and its thick crust due to the increased thickness of the granitic layer. The main units that comprise this tectonic region are Garm, the Pamirs, Tien Shan, and Altai-Sayan mountains.

The western most part of this region is Garm which is the second most seismically active region in the USSR. Earthquakes are found to occur as deep as 250 km. Ritsema (1966) reviews many fault plane solutions, finding that the

horizontal stresses are compressional in both the crust and mantle. However, the deep earthquakes (depth = 150-250 km), the most predominant motion is thrust faulting. The Pamirs, the region east of Garm, consists of a high plateau of folded Cenozoic sediments. This region is also noted for its high seismicity. Most earthquakes are generally confined to the crust and occur at a depth of less than 70 km. The predominant focal mechanisms found in this region are thrust faults and left lateral strike-slip faults (Molnar, et al., 1973). Vol'vovskii and Vol'vovskii (1978) publish three cross sections taken along the Pamir DSS profile. From these profiles, the uppermost layer has a thickness of 30 to 40 km with a P-wave velocity of 6.4 km/sec. The depth of the Moho varies from 50 to 70 km and has a Pn velocity of 8.2 km/sec.

Tien Shan lies to the northwest of the Pamirs and is also characterized by a high level of crustal seismicity. Molnar and Tapponier (1975) find both thrust and strike-slip events in this region. However, thrust faulting is predominate.

The Altai-Sayan mountain region lies to the northeast of Tien Shan. Like the rest of Russian Central Asia, the Altai-Sayan region is seismically active. This region lies just to the northwest of Mongolian Altai which has been the site of several large earthquakes. The focal mechanisms of both 1905 earthquakes (Ms = 7.9 and Ms = 8.25) suggest that they are pure strike-slip (Okal, 1977) and the mechanism of

the 1957 (Ms = 8.0) suggests a left lateral strike-slip with a component of thrust (Okal, 1976).

The average deep seismic sounding model for Russian Central Asia has a sedimentary layer of approximately 4 km with a P-wave velocity of 4.4 km/sec. The granitic layer has a thickness of 28 km with an average P velocity reported to be 5.5 km/sec. The basaltic layer has an average thickness of 30 km with a P velocity of 6.5 km/sec (Vol'vovskii and Vol'vovskii, 1978). However, data from recent Russian translations indicate a low velocity ayer in the crust for both Garm (Chepkunas, 1971) and Tien Shan (Nersesov, et al., 1970a). The top of this layer is located at a depth of 14 km and is approximately 12 km thick. P- and S-wave velocities are 5.5-5.7 km/sec and 3.2-3.4 km/sec respectively. Nersesov, et al. (1970b) state that the layer above this low velocity zone has P and S velocities that are, respectively, 0.4-0.5 and 0.25-0.3 km/sec higher than those found in the low velocity layer.

CRIMEAN-CAUCASUS

The Crimea-Caucasus region includes the Crimean Mountains, the Caucasus Mountains, the Black and the Caspian Seas. This is a region of alpine folding that formed at the turn of the Tertiary and during the Quaternary. This region is characterized by significant fluctuations in the thickness of the sedimentary layer as well as the consolidated strata. The crustal thickness ranges from 18 km in the

Black Sea to greater than 55 km in the Caucasus. Thin crust occurs when the sedimentary layer increases to 15-20 km and lies directly on thin basaltic layers. A thicker crust occurs when the basaltic crust thickens. Where this occurs, the velocity in the lower part of this basaltic layer increases to 7.5 km/sec, possibly indicating a basalt-eclogite composition. The crust in this region is broken into different blocks by deep faults. Each block has a slightly different geologic history.

This region is marked by zones of high seismic activity which are located in the areas of large variation in crustal thickness (Belyaevskii, et al., 1972). To the north of the Black Sea is an earthquake zone which dips at an angle of 60 degrees beneath Crimea. This focal zone is believed to be related to a fault that penetrates the crust down to a depth of 40 km. Seismic activity also occurs in the middle of the Caspian Sea where the crust changes from a continental crust to a transitional crust. This entire region has experienced uplifting due to the Alpine orogeny. In general, the present seismic activity of this zone increases in regions where the crustal blocks have greatly subsided.

The Carpathian fold is a region of highlands. Sollogub, et al. (1973a) conclude that the depth of the Moho is approximately 30 km under the Inner Carpathians, and increases under the mountain structures but never exceeds 45 to 48 km. Belyaevskii, et al. (1972) reports that the Carpathian fold system is characterized by a deep basement (7 to 9 km)

composed of primarily Precambrian gneiss and schist. In the axial zone, the depth of the Moho does not generally exceed 46-48 km.

In the Crimea, folding occurred in the Jurassic and Cretaceous and was followed by uplift and faulting in the late Tertiary and Quaternary. Along the southern coast of Crimea there is present-day movement along normal faults. Piwinskii (1979) summarizes DSS findings which indicate a flat Moho with crustal thickness between 39 and 41 km.

The Caucasus Mountains have the thickest crust in the Alpine region, ranging from 35-57 km. The surface of the Moho exhibits great relief and dips below the Caucasus Mountains indicating the presence of a root zone.

The entire Crimean-Caucausus province is very diverse. Average parameters in the crustal layers are summarized in Vol'vovskii (1978) for the mountainous regions indicating that the average sedimentary layer is 8 km thick with a mean P wave velocity of 4.0 km/sec. The average granitic layer is 15 km thick with an average velocity of 6.1 km/sec. The average basaltic layer is 27 km thick with a velocity of 6.8 km/sec. The average crustal thickness is 50 km with a Pn velocity of 8.2 km /sec. Similarly, the Black Sea has an average crustal thickness of 25 km. The sedimentary layer has an average thickness of 10 km. The average P velocity of this layer is reported to be 3.5-3.8 km/sec. The basaltic layer has an average thickness of 23 km with a P wave velocity of 6.4-6.8 km/sec. The Pn velocity is 8.0 km/sec.

The sedimentary layer in the Caspian Sea area is 20 km thick with an average reported P velocity of 3.4-3.6 km/sec. The basaltic layer is approximately 23 km thick with a velocity of 6.6 km/sec. Pn velocities in the basin average 8.0 km/sec.

BAIKAL RIFT ZONE

The Baikal Rift Zone is believed to be a branch of the Central Asiatic seismic belt. In the east near the southern part of the Aldan shield it forks and forms two individual branches. The Dzhugdzhur branch extends toward the Sea of Okhotsk and Verkhoyansk branch swings northwest and stretches toward the Artic Ocean rift system. The most outstanding features of this province are rift systems and a low velocity upper mantle.

In Baikal Rift Zone the most reliable indication of active rifting comes from high seismic activity that indicates extensional tectonics. The crust is 34-35 km thick under the deeper part of the Baikal depression but is as thick as 42 to 46 km under adjacent regions (Puzyrev, et al., 1973).

Puzyrev, et al. (1978) compiled both explosion and earthquake seismology data to characterize the upper mantle. The central part of the rift zone has a highly variable crustal thickness compared with neighboring regions which are less tectonically active. In the rift zone depths to the Moho vary form 34 to 48 km. Nearby in the Siberian

Platform and in Zabaikalye the crust varies in thickness from 37 to 39 km and 39 to 42 km respectively.

Earthquakes occur in this region as both mainshock-aftershock sequences and as swarms (Baraguzin area). Golenetsky and Misharina (1978) believe that the swarms occur in the regions that previously have been seismically active. These swarms are of various durations, some lasting over a period of several years. Additionally, smaller earthquakes are believed to be located primarily in the upper part of the crust.

Vol'vovskii (1978) gives average crustal structures for some areas in this region. In the Enisei meganticlinorium the granitic layer has an average P-wave velocity of 6 km/sec, the basaltic layer has an average velocity of 6.8 km/sec, and the consolidated crust has an average velocity of 6.4 km/sec. In the areas of Baikal folding, the average crustal thickness is 42 km. There is no sedimentary layer. The granitic layer is 18 km thick with a velocity of 6.0 km/sec while the basaltic layer is 24 km thick with a velocity of 7.8 km/sec. The Baikal Depression has a total crustal thickness of 36 km. The water layer is 2 km, the sedimentary layer is 4 km thick with a velocity of 5.3 km/sec, the granitic layer is 11 km thick with a velocity of 6.3 km/sec, and the basaltic layer is 19 km thick with a velocity of 6.7 km/sec. The Pn velocity under Lake Baikal is reported to be 7.7 km/sec.

PACIFIC TRANSITIONAL ZONE

The Pacific Transitional Zone, a region of high seismicity, includes the Kamchatka, the Kurile Islands, Sakhalin, and the Sea of Okhotsk. During the Cretaceous this province was a geosyncline. During the transition from Upper Cretaceous-Tertiary the easternmost part of the region was uplifted. In the Olegocene this uplift was complicated by a system of northwesternly trending deep faults. This resulted in individual zones of uplift and downwarp which shaped the mid-Kamchatka trough, the Eastern Kamchatka Range and the Western and Eastern Kamchatka foredeeps (Fedotov, et al., 1971). The Kurile-Kamchatka volcanic arc and trench, which is the easternmost part of the province, began developing in the late Tertiary. Tuyezov, et al. (1968) believe that the westernmost border of this geosynclinal region coincides with the north and northwest limits of the Yuzhno-Okhotsk depression and with the east Kamchatka anticlinorium. The westernmost part of the Pacific Transitional zone is a folded region which includes Primor'e, Sakhalin, Okhotsk Volcanic Region and western Kamchatka. The folding ended by the end of the Tertiary.

The Pacific Transitional Zone is characterized by a highly variable crustal thickness ranging from 8-43 km. There are four types of crust found in this region; continental, subcontinental, suboceanic, and oceanic. These crustal structures differ from each other with regard to the depth of the Moho and the number of crustal layers. There

is a general trend of crustal thinning in the direction of the ocean.

In Kamchatka, most faults are parallel to the Kurile Trench. Earthquakes associated with these faults are believed to be related to the subduction of the Pacific Plate. The Kronohi-Krutogorova fault zone is the only major fault system that trends in an east-west direction. In the Kronoki peninsula in east Kamchatka, the faults are right-lateral with a maximum offset of 20-25 km. In the western portion of this fault zone the primary motion is left-lateral.

The Kurile Trench is one of the most seismically active areas in the world and accounts for 80% of the seismicity in the USSR. Earthquakes are found as deep as 650 km.

Piwinskii (1979) in his summar of DSS for the Sea of Okhotsk reports that the depth of the Moho varies between 8 and 26 km. Rodnikov (1973) reports that when the granitic layer is observed it is found at a depth of 4 to 5 km. It is usually 6-7 km thick under the major ridge and reaches a thickness of 5-6 km under the minor ridge of the arc. Vol'vovskii (1978) finds that the average cross section for the Kurile-Kamchatka trench has a 14.5 km thick crust. There is a water layer with an average depth of 3.5 km. The sedimentary layer is .5 km thick with an average P-wave velocity of 2.4 km/sec. A granitic layer is absent. The basaltic layer has an average thickness of 14 km with a P-wave velocity of 6.6 km/sec. The average Pn velocty was reported to be 8.0 km/sec.

Piwinksii (1979) reports the following conclusions about the crust in Kamchatka. The crustal thickness varies from 30-42 km but is thickest in central Kamchatka. The crust thins to the east and the west. There are three layers including a sedimentary-volcanoclastic sequence, a granitic-metamorphic complex and a basaltic sequence. Additionally, several deep fractures penetrate the crust and upper mantle.

Sakhalin is a region of continental crust. Gainanov, et al. (1968) report that beneath Sakhalin the depth to the Moho reaches 32 km in Sakhalin compared to 12 km to the east and 25 km to the west of the island. There are four layers that exist within the crust with average velocities of 4 km/sec, 5 km/sec, 6.1 km/sec, and 7.4 km/sec.

Finally, Vol'vovskii (1978) reports that average crustal thickness for regions of Cenozoic folding is 28 km. This is considered to be average for both Kamchatka and Sakhalin. The sedimentary layer averages 4 km with a P velocity of 2.5 km/sec. The granitic layer has an average thickness of 10 km with an average P velocity of 6 km/sec. The basaltic layer is 14 km thick with an average P velocity of 6.8 km/sec. The average Pn velocity is 7.9 km/sec.

IV. DATA

The data set used in this study were seismograms of Rayleigh waves generated by presumed nuclear explosions located within the USSR. These data were recorded by WWSSN stations in both Europe and Asia. Several thousand seismograms were reviewed and 132 high quality records were digitized for further analysis. This data base encompasses records from 20 different stations that recorded 25 explosions from sources located at Novaya Zemyla, Semipalatinsk, northern and western Kazakh. In total, data were obtained from 41 distinct source-station pairs that traverse the various provinces of Eurasia (Figure 2). Table 1 lists all of the events used in this study.

The data set of 132 seismograms were carefully hand digitized and checked to insure that the digital record precisely overlaid the photocopy. The records were corrected for trace skew, magnification and were finally interpolated to a uniform time spacing of 0.5 sec. Figure 3 shows an example of the quality of the data used in this study.

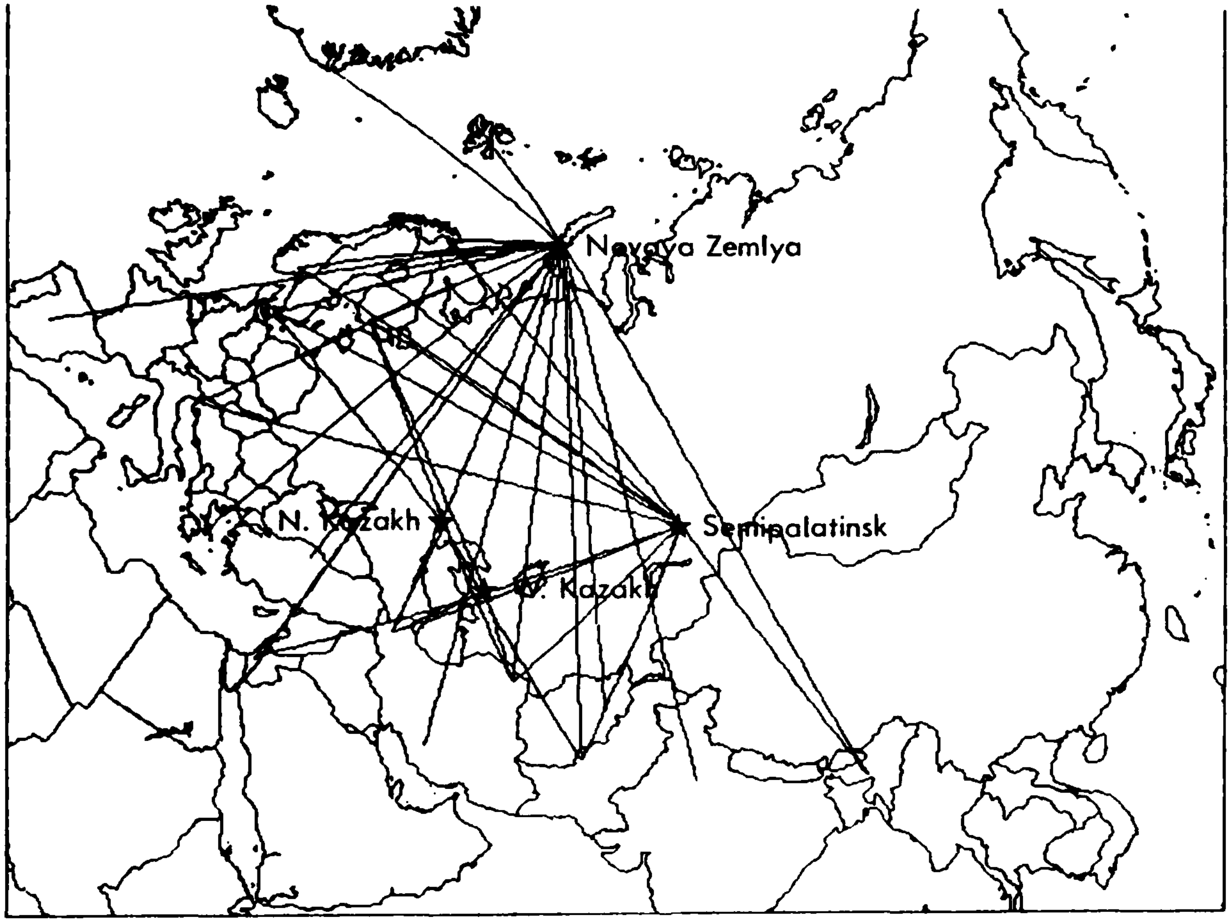

Figure 2. Great circle paths for the surface wave data used in this study.

TABLE 1. EVENTS USED IN THIS STUDY.

DATE	TIME	LATITUDE(N)	LONGITUDE(E)	LOCATION	M_b	M_S
2/13/66	4:57:58	49.82	78.13	Semipalatinsk	6.1	
12/18/66	4:57:58	49.93	77.73	Semipalatinsk	5.8	
7/15/67	3:26:58	49.88	78.16	Semipalatinsk	5.4	
10/21/67	4:59:58	73.40	54.42	Novaya Zemlya(N)	5.9	
7/12/68	12:07:58	49.77	78.09	Semipalatinsk	5.3	
9/29/68	3:42:58	49.82	78.18	Semipalatinsk	5.8	
12/6/69	7:02:57	43.83	54.78	Kazakh(W)	5.8	
10/14/70	5:59:57	73.31	54.89	Novaya Zemlya(S)	6.9	5.1
12/23/70	7:00:57	43.81	54.82	Kazakh(W)	6.6	
9/27/71	5:59:55	73.40	55.10	Novaya Zemlya(N)	6.5	5.2
12/12/71	7:00:57	43.87	54.78	Kazakh(W)	6.6	
12/22/71	6:59:56	47.87	48.22	Kazakh(N)	6.0	
8/20/72	2:59:58	49.46	48.18	Kazakh(N)	5.7	
8/28/72	5:59:57	73.30	55.10	Novaya Zemlya(N)	6.3	4.7
11/2/72	1:26:58	49.91	78.84	Semipalatinsk	6.1	
12/10/72	4:26:58	49.85	78.10	Semipalatinsk	5.6	
7/23/73	1:22:58	49.99	78.85	Semipalatinsk	6.1	4.7
9/12/73	6:59:54	73.30	55.20	Novaya Zemlya(N)	6.8	5.0
8/29/74	9:59:56	73.37	55.09	Novaya Zemlya(N)	6.4	5.0
11/2/74	4:59:57	70.81	53.91	Novaya Zemlya(N)	6.4	5.3
8/23/75	8:59:57	73.34	54.50	Novaya Zemlya(N)	6.3	4.9
10/18/75	8:59:56	70.84	53.69	Novaya Zemlya(N)	6.7	5.1
10/21/75	11:59:57	73.35	55.08	Novaya Zemlya(N)	6.6	
1/15/76	4:46:57	49.80	78.25	Semipalatinsk	5.2	
7/29/76	4:59:58	47.78	48.12	Kazakh(N)	5.9	4.4

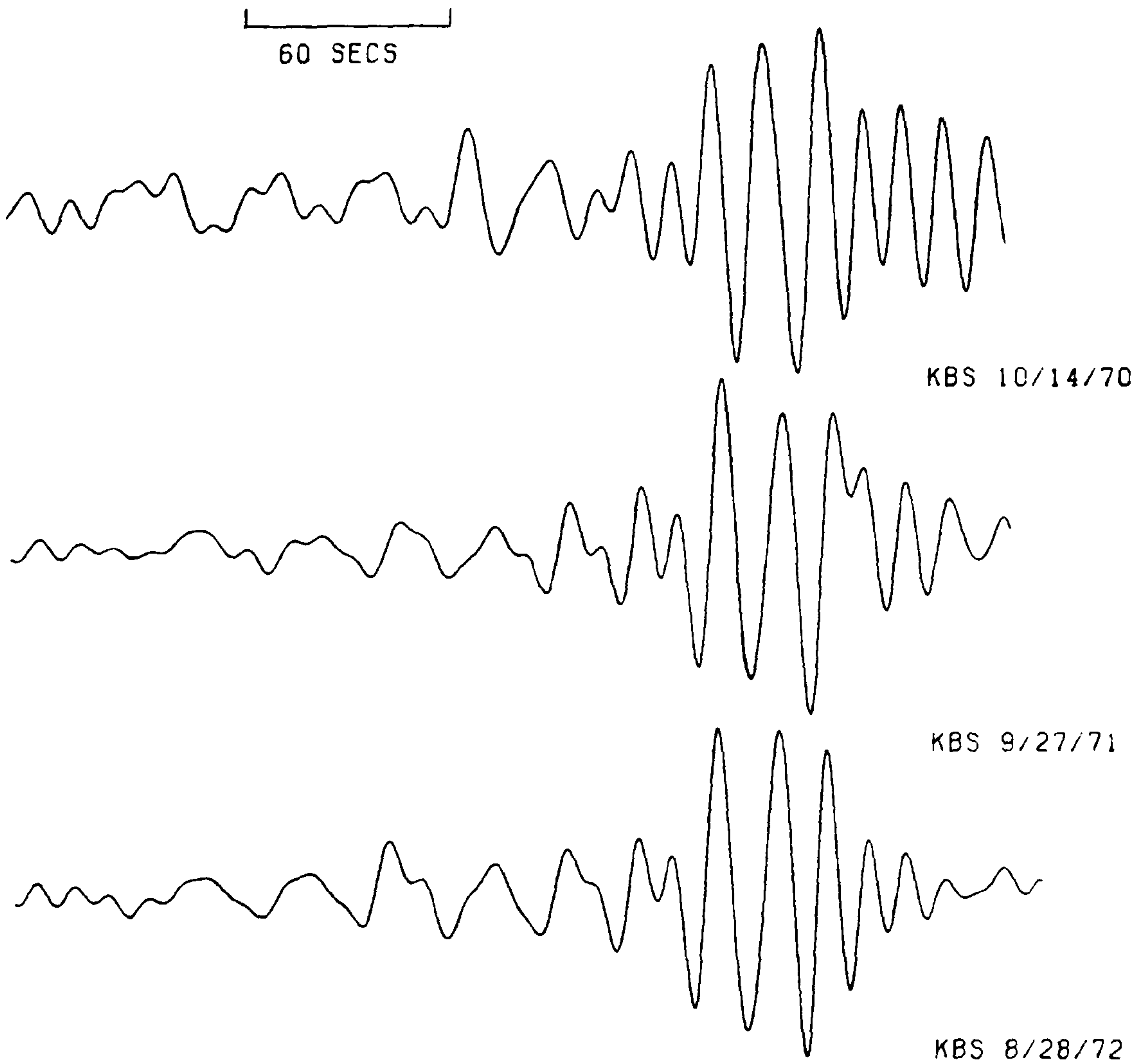

Figure 3. Examples of the quality of the surface wave data used in this study.

V. DATA ANALYSIS

5.1 DISPERSION

The observed Rayleigh waves used in this study may contain both higher mode and multi-pathed arrivals. Before the phase velocity curves can be derived from these data, it is first necessary to isolate and utilize only the data from the mode of interest. This has been accomplished by first constructing plots of frequency vs. group velocity, Figure 4. At each frequency, this figure represents the envelope of the narrow band passed filtered seismogram. Gaussian, zero phase shift filters have been used in the analysis. The form of the Gaussian filter is:

$$G(\omega,\omega_o) = \exp\{-\alpha[(\omega-\omega_o)/\omega_o]^2\} \qquad (1)$$

where ω_o is the center frequency and α is the width of the filter. The Hilbert transform of the Gaussian filtered record was calculated in order to obtain the amplitude envelope of the filtered record. The group velocity for a particular frequency is simply calculated from the distance the wave traveled and the group arrival time. In this analysis the seismograms have been corrected for instrument response. The initial phase of the source has been assumed to be zero.

The primary reason for computing the group velocity dispersion curves was to identify both multipathing and

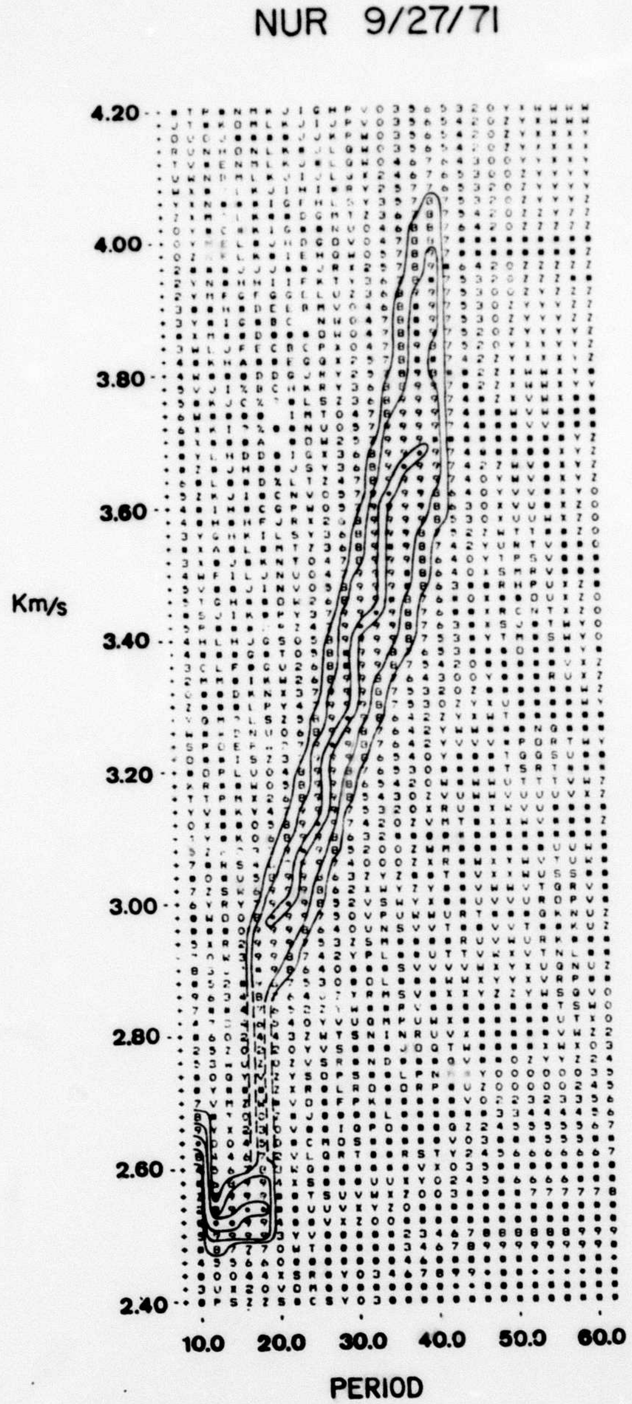

Figure 4. Example of the group velocity analysis plot used to identify distinct modes. This plot was constructed by narrow band pass filtering the raw seismogram at each period and computing the envelope. The symbols along each vertical row of the plot represent the amplitude of the envelope, and "*, 9, 8 . . . 1, Z, Y, X . . . A" represent the range from maximum to minimum and "#" represents a local maximum.

overtones. This is a very important step in calculating the phase velocity dispersion curves. It is necessary to window the seismogram in time so that all overtones or multipathed arrival are separated from each other. If this is not correctly done, multiple arrivals of the same frequency occur within a single window and the derived phase data are very unreliable. In the course of doing this analysis, we seldom found well developed overtones in the period range 5-100 sec. The exception was for the path between the Caspian Sea test site and the WWSSN station MSH. Figure 4 shows a typical group velocity curve for the paths analyzed. Overlapping phase velocity curves were next computed from the data by time windowing coherent group arrivals as defined by the group velocity curves. The flow of this process is shown on Figure 5.

An additional consideration in windowing the data for the phase velocity analysis is noise. In general, we found that the hand digitized records have a maximum reliable dynamic range of about 30-35 db. Frequencies with amplitudes 35 db below the maximum amplitude were excluded from the analysis. Since the group arrival windows were selected on the basis of identifying uniform peaks in the narrow band-pass filtered records, the signal to noise ratio was always greater than unity.

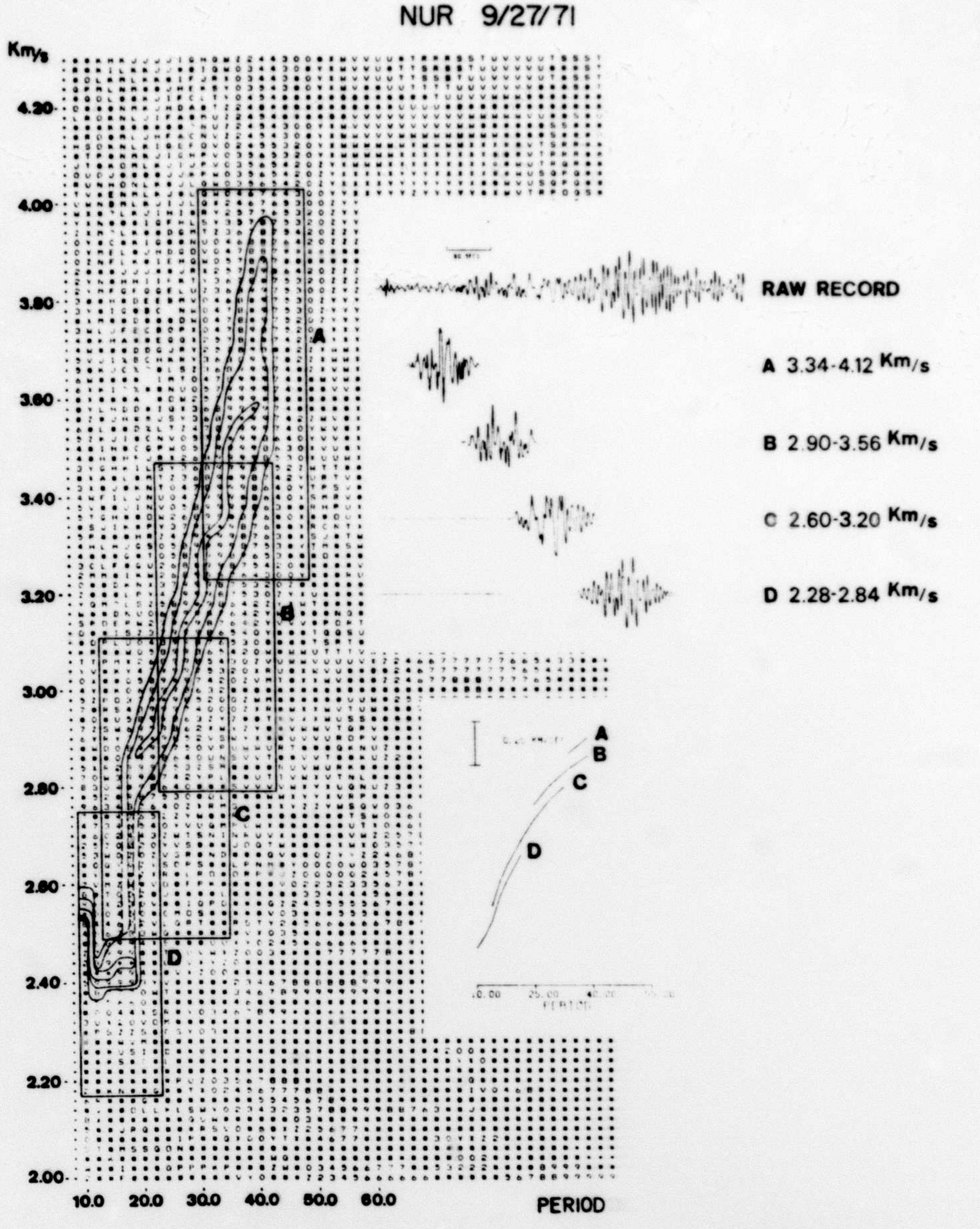

Figure 5. Analysis process for reducing a raw seismogram to a final phase velocity curve. The first step is to identify group arrival times for the mode and period range of interest (boxes A to D). By windowing the record in this manner (records A to D) higher modes or multipathed arrivals can be excluded from the analysis. Finally, phase velocities are computed from the windowed records (curves in the lower right). For clarity these four phase curves have been offset from each other by 0.1 km/s.

The Rayleigh wave phase velocity for each frequency, ω, can be determined using a one station method (Brune, Nafe, and Oliver, 1960; Weidner, 1974):

$$C = \frac{\omega x}{\phi_{obs} + 2\pi N - \phi_{ins} - \phi_s + 3\pi/4} \tag{2}$$

where x is the epicentral distance, ϕ_{obs} is the observed phase, ϕ_{ins} is the phase delay of the instrument, ϕ_s is the initial phase of the source (assumed to be zero due to explosion source), and N is an integer. The value of N must be derived from other considerations. By starting the analysis with long periods the correct multiple of 2π is usually obvious.

The phase velocities have been calculated for the event-station pairs shown on Figure 2. For each path all values were then averaged and standard deviations were then calculated. Figures 6, 7, 8 and 9 show examples of the derived phase velocity curves from this study.

5.2 INVERSION

The starting model for the inversion was a path average model obtained from the literature search. The path average model was obtained by first calculating a great circle path from the source to the receiver. Latitudes and longitudes were calculated in 100 kilometer intervals. The most appropriate velocity structure for this 100 kilometer path length was obtained from the models discussed previously. When the literature search did not yield S-wave velocity

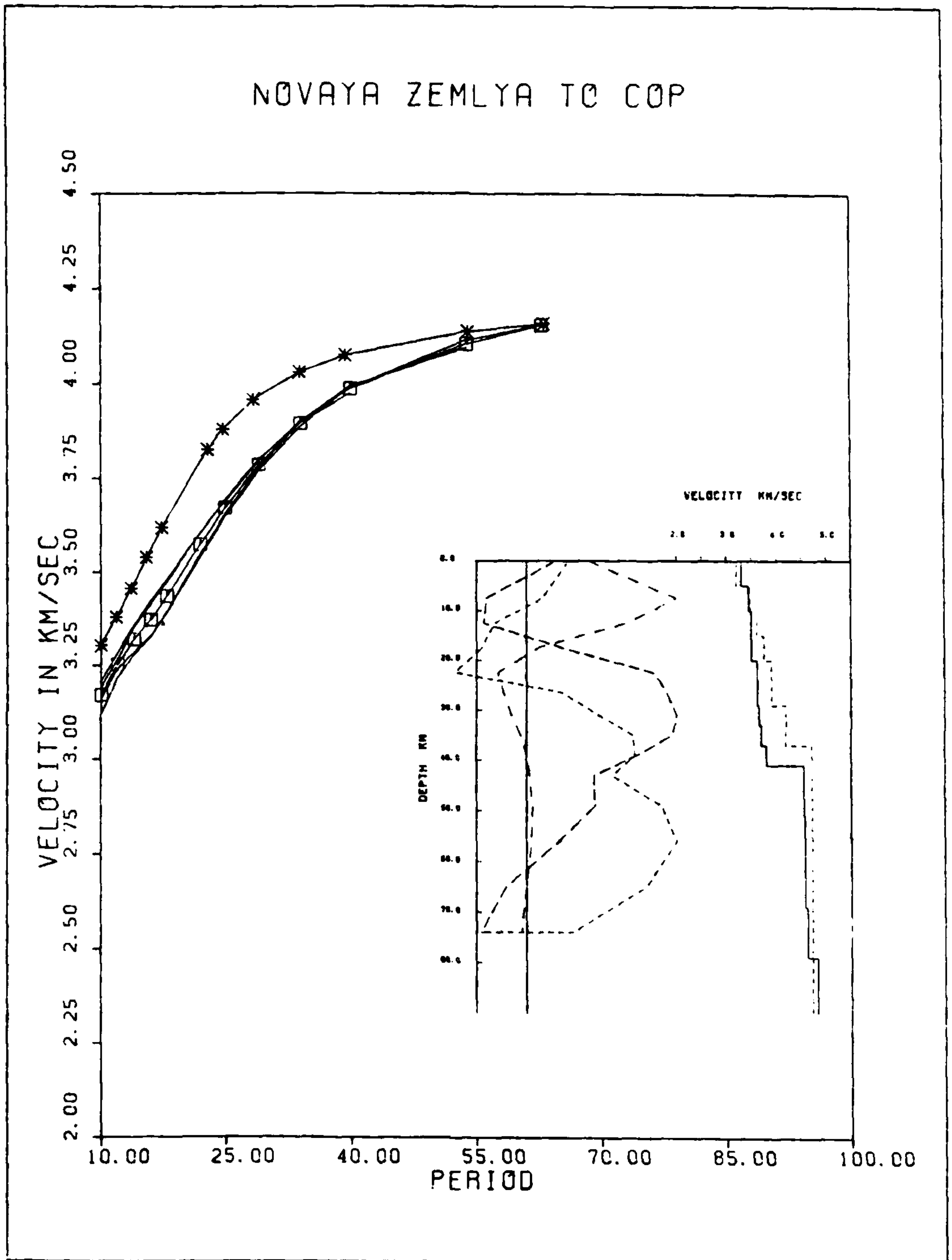

Figure 6. Phase velocity curves and velocity models derived from observations and from the literature. The phase curve indicated with a "*" was computed from a starting model (dashed line on the inset model) based on the literature. The phase curve indicated with a " □ " represents the mean phase velocity curve computed from the individual determinations from each observation. The crustal model derived from these phase curves is indicated with the solid line on the inset model. The dashed curves to the left of the models are the averaging kernals, as discussed in the text.

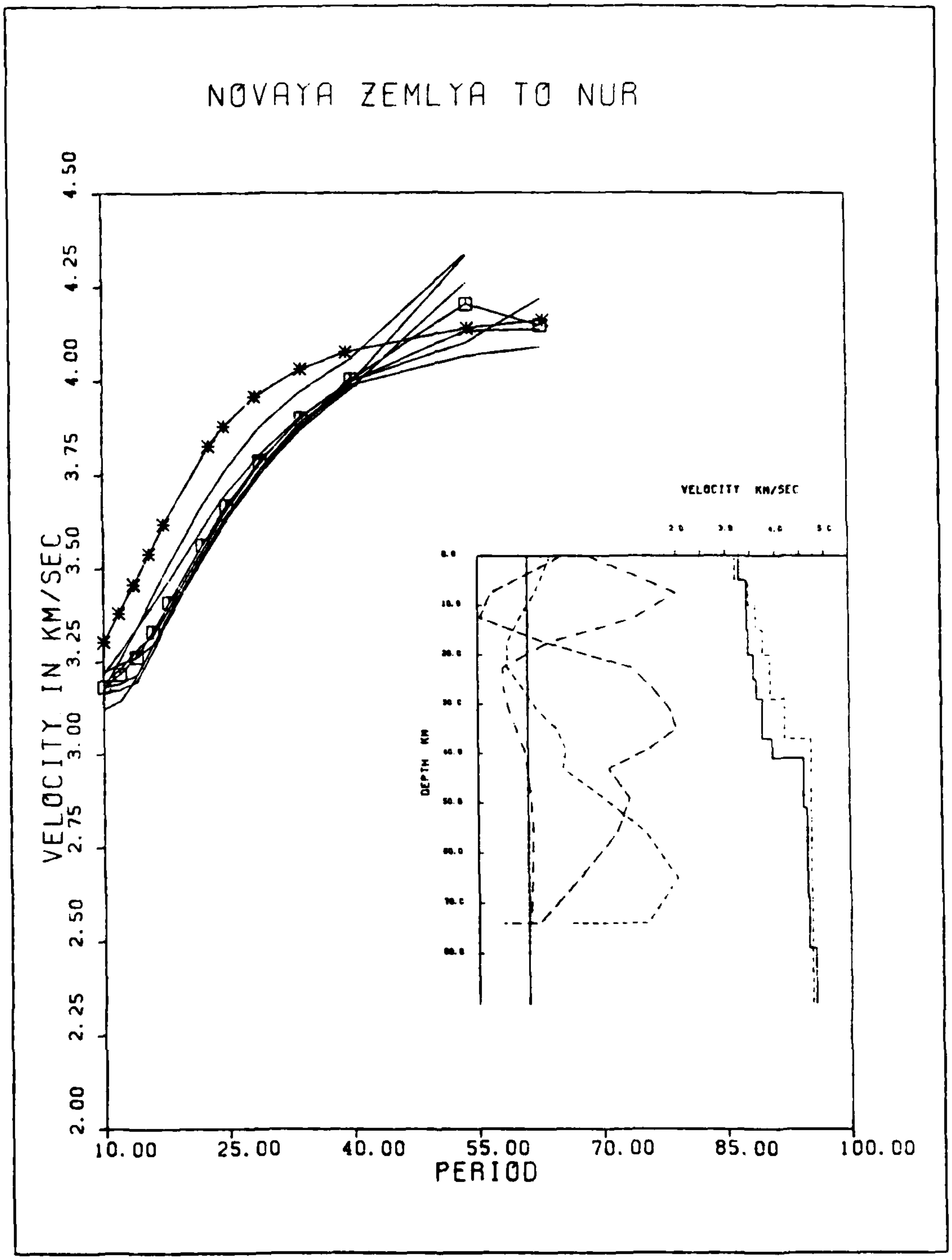

Figure 7. Phase velocity curves and velocity models derived from observations and from the literature. See Figure 6 for a full description.

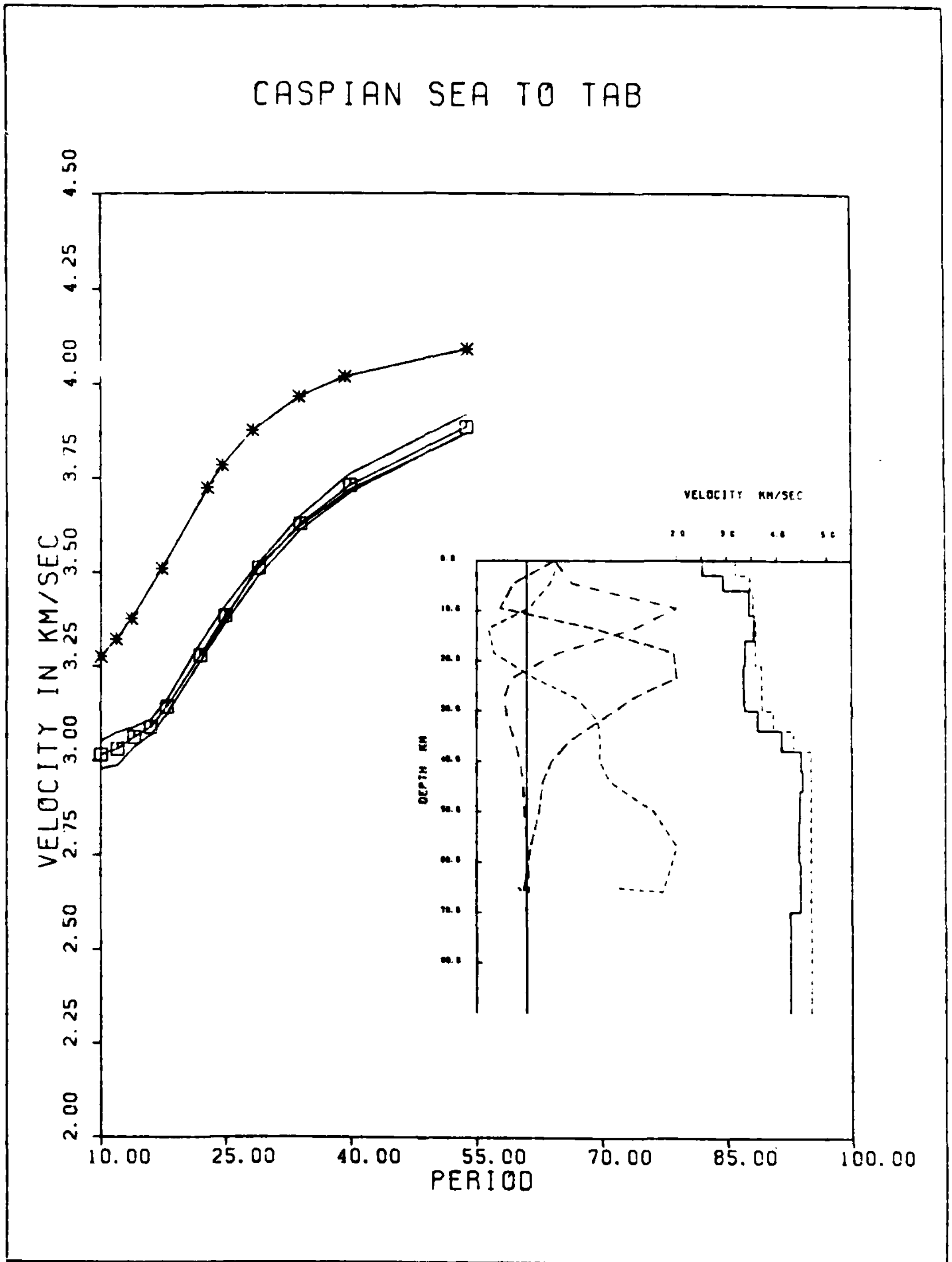

Figure 8. Phase velocity curves and velocity models derived from observations and from the literature. See Figure 6 for a full description.

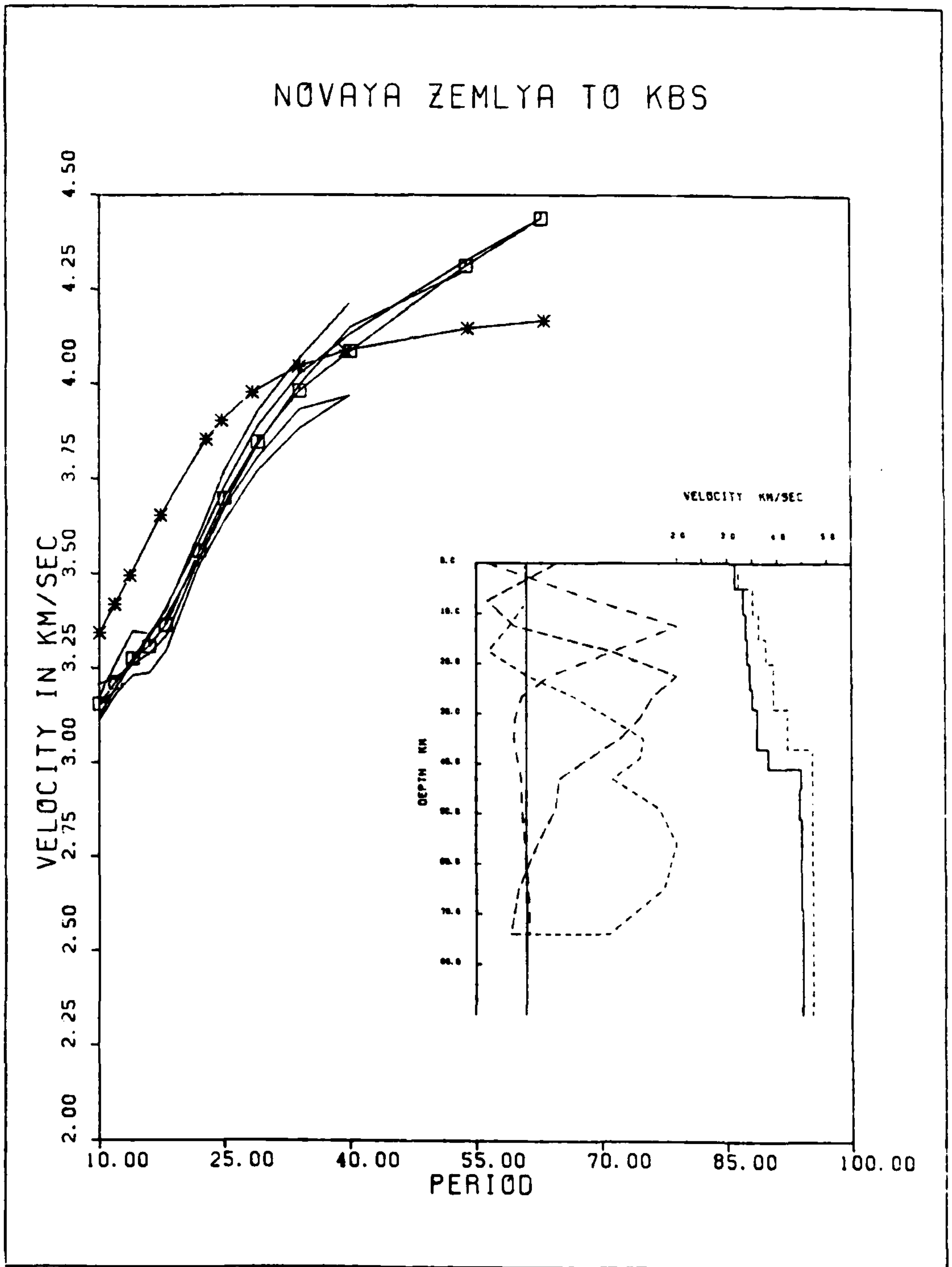

Figure 9. Phase velocity curves and velocity models derived from observations and from the literature. See Figure 6 for a full description.

data, starting velocities were calculated for the P-wave model with the assumption of Poisson's ratio of 0.25. The simple starting model of a 3 layer crust over an upple mantle half space was parameterized by 15 distinct layers. The starting velocity model was then calculated by averaging the properteis of these thin layers for each path segment.

In the inversion discussed below the starting model was improved by altering the layer velocities and not the layer thicknesses. This over parameterization of the model avoids artifically constraining the layer thicknesses as would be the case if only 3-layers had been used. If the inversion finds that the original 3-layer crust contained inappropriate layer thicknesses, velocities in the thin layers can be altered to effectively migrate the boundaries.

The phase velocity curves discussed above were inverted with a damped generalized inverse technique (e.g., Franklin, 1970; Wiggins, 1972). We assumed the data and the model are related by:

$$A = MD \tag{3}$$

where M and D are vectors representing, respectively, the desired perturbation to the starting model and the difference between the real and the model data. A is the matrix of partial derivitives that maps M into D. The model is then calculated using:

$$M = A^T (AA^T + (r/(1-r))V)^{-1} D \tag{4}$$

The range of r extends from 0 to 1. This variable controls the stability of the solution. As r tends to zero, the solution moves smoothly to the undamped inverse. The matrix V is the data variance matrix. The diagonal elements are the variance of each determination of the phase velocity, computed from the standard deviations of the determinations at each frequency. The off-diagonal terms describe the covariance between dfferent frequencies. Because of the window characteristics used in the data processing, the covariance terms are not all zero. However, the covariance between periods at opposite ends of the frequency band is near zero. We therefore have tapered the covariance matrix with a Gaussian function to approximate the data smoothing inherent in the processing. Finally, the average kernal for layer i is given by:

$$F_i = A^T(AA^T + (r/(1-r))V)^{-1} AE_i \tag{5}$$

where E_i is the unit vector in the ith direction. The averaging kernal describes the resolution of the derived model.

If the starting model requires large changes (10-20% in either the velocity of the layer or the effective layer thickness) to fit the data, the derived model may have a large gradient across the Moho, instead of a distinct boundary, or large velocity reversals. These artifacts result from both the width of the averaging kernals and instability. When these problems have been encountered the

starting models have been modified by changing layer thicknesses and velocities so that the final derived models approximate a simple crust with a distinct Moho. Examples of the phase data, starting models and derived models are shown in Figures 6, 7, 8 and 9. The dashed lines to the left of each inset model on Figures 6, 7, 8 and 9 represent the S-wave averaging kernals for the upper, middle and lower portions of the model. These kernals show that the upper crustal velocities represent an average over a depth range of 10-15 km, whereas the velocites in the lower crust and upper mantle average over a much broader depth range.

5.3 COMPARISON WITH DATA

The adequacy of these models to describe the observations has been tested by computing synthetic seismograms for comparison with the data. These seismograms have been computed for the derived models with a normal mode program (Harkrider, 1964, 1970). On the basis of the group velocity analysis discussed above, only the fundamental mode for the period range 5-100 sec was included in the calculations. The seismic source was assumed to be a shallow (depth = 0.5 km) siotropic point source function. Both the observations and the synthetics have been low pass filtered with a cutoff period of 5 sec. Comparison of the synthetic seismograms with the observations are shown on Figure 10. As seen in this figure, the synthetic seismograms are in very good agreement with the observations. The maximum time

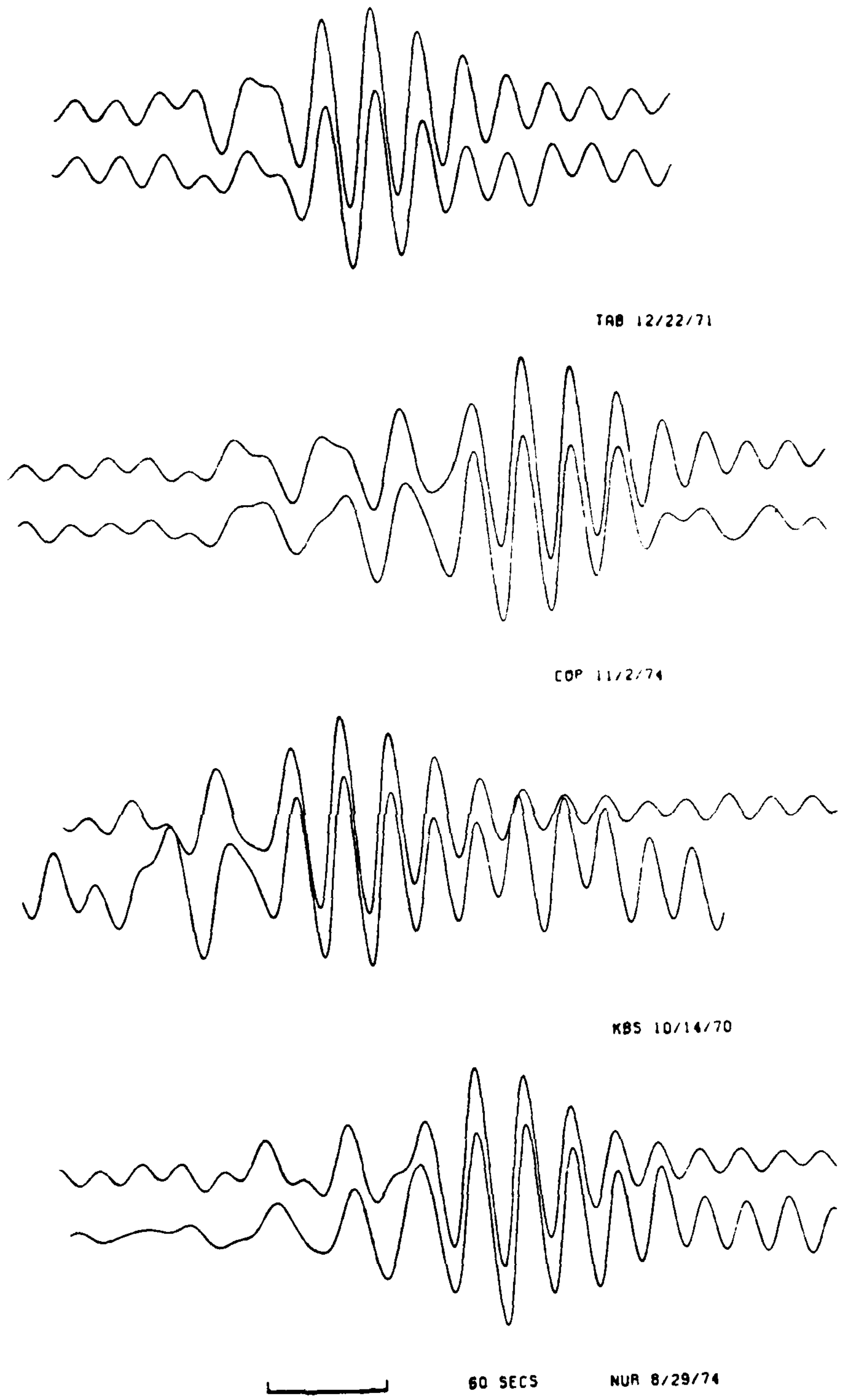

Figure 10. Observation (lower) and synthetic (upper) surface waves. The synthetics have been computed from the models indicated on Figures 7 through 9. The maximum time shift required to align the synthetics with the observations is 2 sec.

shift required to align the synthetics with the observations is 2 sec. This demonstrates that N in Equation 2 is unambiguously defined by the data.

REFERENCES

Alverson, D.C., D.P. Cox, A.J. Woloshin, C.R. Lewis, M.J. Terman, C.C. Woo and C.H. Maxwell, 1969, Atlas of underground nuclear testing, Vol. 2, Tectonics (prepared by U.S.G.S.)

Belyaevskii, N.A., A.A. Borisov, et al., 1972, The internal structure of the earth's crust, Priroda, 4, p. 32-43 (English translation).

Borodulin, M.I., L.T. Kalyuzhnaya, M.G. Manyuta, S.S. Mikul'skii, V.B. Sollogub, N.T. Turchanenko, A.V. Chekunov, and M.V. Chirvinskaya, 1978, Deep structure of the Dnepr-Donets aulacogen. In: Sollogub and Chekunov (editors), Structure of the Earth's Crust and Upper Mantle Plotted from Data of Seismic Studies. Academy of Sciences of the Ukrainian SSR, Institute of Geophysics, Naukova Dumka Publisher, Kiev, 1977: 226-239, UCRL-TRANS-11392.

Brune, J.N., J.E. Nafe, and J. Oliver, 1960, A simplified method for the analysis and synthesis of dispersed wave trains, Journal of Geophysical Research, 65, p. 287-304.

Chepkunas, L.S., 1971, Identification of a low velocity zone in the earth's crust in the Garm region determined from attenuation of body waves from local earthquakes: Experimental Seismology, Moskva, Izd-vo "Nauka," p. 203-210 (English condensation).

Fedotov, S.A., 1968, on Deep Structure, Properties of the Upper Mantle, and Volcanism of the Kurile Kamchatka Island Arc According to Seismic Data. In: L. Knopoff, C.L. Drake, P.J. Hart (editors), The Crust and Upper Mantle of the Pacific Area, American Geophysical Union, Monograph 12, 131-140.

Fedotov, S.A., A.M. Bagdasarova, I.P. Kuzin, and R.Z. Tarakanov, 1971, Earthquakes and the deep structure of the South Kurile Island Arc, Israel Program for Scientific Translations, Jerusalem, 239 pages.

Franklin, J.N., 1970, Well-posed stochastic extensions of ill-posed linear problems, Journal of Mathematical Analysis and Applications, 31, p. 682-716.

Gainanov, A.G., S.M. Zverev, I.P. Kosminskaya, M. Kh. Livshitz, A.P. Milashin, O.N. Soloviev, P.A. Stroev, P.M. Sichev, I.K. Tuyezov, Yu. V. Tulina, and E.E. Fotiadi, 1968, The crust and the upper mantle in the Transition Zone from the Pacific Ocean to the Asiatic Continent; In L. Knopoff, C.L. Drake, P.J. Hart (editors), The Crust and Upper Mantle of the Pacific Area: American Geophysical Union, Monograph 12, 367-379.

Given, J.W. and D.V. Helmberger, 1980, Upper mantle structure of northwestern Eurasia, J. Geophys. Res., 85, 7183.

Golenetsky, S.I., and Misharina, L.A., 1978, Seismicity and

earthquake focal mechanisms in the Baikal rift zone, Tectonophysics, 45, 7185.

Harkrider, D.G., 1964, Surface waves in Multilayered media I. Rayleigh and Love waves from buried sources in a multilayered elastic half-space, BSSA, 54, 627-679.

Harkrider, D.G., 1970, Surface waves in multilayered media II. Higher mode spectra and spectral ratios from point sources in plane-layered earth models, BSSA, 60, p. 1937-1987.

King, D.W. and G. Calcagnile, 1976, P wave velocities in the upper mantle beneath Fennoscandia and Western Russia, Geophys. J. R. Astr. Soc., 46, 407-432.

Kosminskaya, I.P. and N.I. Pavlenkova, 1979, Seismic models of inner parts of the Euro-Asian continent and its margins. In: C.E. Keen (editor), Crustal Properties across Passive Margins. Tectonophysics, 59, 307-320.

Masse', R.P. and S.S. Alexander, 1974, Compressional velocity distribution beneath Scandinavia and Western Russia: Geophysical Journal of R.A.S., 39, 587-602.

McCowan, D., .P. Glover, and S. Alexander, 1978, A crust and upper mantle model for Novaya Zemlya from Rayleigh wave dispersion data: B.S.S.A., 68, 1651-1662.

Molnar, P., T. Fitch, and F. Wu, 1973, Fault plane solutions of shallow earthquakes and contemporary tectonics in Asia, Earth and Planetary Science Letters, 19, 101-112.

Molnar, P. and P. Tapponnier, 1975, Cenozoic tectonics of Asia: Effect of a continental collision, Science, 189, p. 419-426.

Nersesov, I.L. and L.S. Chepkunas, 1970a, Discovery of a low-velocity zone in the Earth's crust in Southern Tien-Shan, Proceedings of the Tenth Assembly of the European Seismological Commission, Moskva, AN SSSR, Sovetskiy geofizicheskiy komitet, 1, 197-20. (English condensation).

Nersesov, I.L. and L.S. Chepkunas, 1970b, The totality of criteria determining the presence of a low velocity zone in the crust in the Garm region of Soviet Central Asia, A N SSSR, Doklady, 193, 323-326 (English condensation).

Okal, E.A., 1976, A surface wave investigation of the rupture mechanism of the Gobi-Altai (December 4, 1957) Earthquake, Physics of the Earth and Planetary Interiors, 12, 319-328.

Okal, E.A., 1977, The July 9 and 23, 1905, Mongolian Earthquakes: A surface wave investigation, Earth and Planetary Science Letters, 34, 326-331.

Piwinskii, A.J., 1979, Deep structure of the Earth's crust and upper mantle in the U.S.S.R. according to Geophysical and seismological data, Part I: Lawrence Livermore Laboratory UCID-18099.

Puzyrev, N.N., M.M. Mandelbaum, S.V. Krylov, B.P. Mishenkin, G.V. Krupskaya and G.V. Petrick, 1973, Deep seismic investigations in the Baikal rift zone, Tectonophysics, 20, 85-97.

Puzyerv, N.N., V.A. Kondrashov, S.V. Krylov, and S.V. Potap'ev, 1978a, First results of deep seismic studies of the earth's crust in the central part of Western Siberia, Geologiya i Geofizika, 11, 82-89 (1969), UCRL-TRANS-1135

Ritsema, A.R., 1966, The fault-plane solutions of earthquakes of the Hindu Kush center; Tectonophysics, 3, 147-162.

Rodnikov, A.G., 1973, The Earth's crust in the northwestern part of the Pacific mobile belt, Tectonophysics, 20, 105-115.

Samowitz, I.R. and D.M. Hadley, 1980, Summary and review of the tectonic structure of Eurasia, Sierra Geophysics Report SGI-R-80-025.

Sollogub, V.B., D. Prosen and Co-Workers, 1973a, Crustal structure of Central and Southeastern Europe by date of explosion seismology; Tectonophysics, 20, 1-35.

Sollogub, V.B., I.V. Litvinenko, A.V. Chekunov, S.A. Ankudinov, A.A. Ivanov, L.T. Kalyuzhnaya, L.K. Kokorina and A.A. Tripolsky, 1973b, New DSS data on the crustal structure of the Baltic and Ukrainian Shields; Tectonophysics, 20, 67-85.

Sollogub, V.B., A.V. Chekunov, A.A. Tripol'skii, L.T. Kalyuzhnaya, and L.I. Gontovaya, 1978, Deep structure of the Ukrainian Shield according to seismic data. In: Sollogub and Chekunov (editors), Structure of the

Earth's Crust and Upper Mantle Plotted from Data of Seismic Studies. Academy of Sciences of the Ukrainian SSR, Institute of Geophysics, Naukova Dumka publisher, Kiev, 1977, 79-104, UCRL-TRANS-11392.

Tuyezov, I.K., P.M. Sichev, R.Z. Tarakanov, and M.L. Krasny, 1968, Structure of the folded areas and recent geosynclines of the Okhotsk Area. In: L. Knopoff, C.L. Drake, and P.J. Hart (editors), The Crust and Upper Mantle of the Pacific Area: American Geophysical Union, Monograph 12, 473-481.

Vinnik, P.P., and V.Z. Ryaboy, 1980, Deep Structure of the East-European platform according to seismic data, in press.

Vol'vovski, I.S., 1978, Seismic structure of the earth's crust in the U.S.S.R.: UCRL-TRANS-11322.

Vol'vovskii, I.S. and B.S. Vol'vovskii, 1978, Cross sections of the Earth's crust in the territory of the U.S.S.R., Plotted from deep seismic soundings: UCRL-TRANS-11324.

Weidner, D.J., 1974, Rayleigh wave phase velocities in the Atlantic Ocean, Geophysics Journal of The Royal Astronomical Society, 36, p. 105-139.

Wiggins, R.A., 1972, The general linear inverse problem: Implication of surface waves and free oscillations for Earth structure. Review of Geophysics and Space Physics, 10, p. 251-285.